Thermal Modeling and Analysis of the NASA/GSFC/LHEA GLAST Science Payload

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1. Work Statement

The NASA/GSFC Laboratory of High Energy Astrophysics (LHEA) requested thermal modeling and analysis support from the Physical Science Laboratory (PSL) for the Gamma-ray Large Area Space Telescope (GLAST) payload in preparation for the upcoming summer 2001 engineering test flight from Palestine, Texas. This support is provided as a project under Task 5 of contract NAS5-98009 (Approval 01-003).

The Principal Science Investigator, Dr. David J. Thompson, requested a thermal analysis focused primarily on definition and determination, specifically with respect to the need for active versus passive thermal control schemes. This analysis is intended to only provide a comfort factor and general design direction to avoid potential temperature extremes before committing the instrument to a balloon flight.

2. Modeling/Analysis Approach

This modeling/analysis was performed in a similar fashion to that PSL routinely does in support of NASA balloon program flights, namely the software[1] and general methodology is similar. Although, this modeling/analysis contains substantially less geometric fidelity than is typically created.

2.1. Geometry

The geometry data used in the creation of the science portion of the thermal model was that provided by Gary Godfrey (SLAC), dated January 31, 2001. Including the balloon, the thermal model contains 804 total (456 nodes, 318 planar elements, 8 surfaces, 3 solids, 16 conductors and 3 heat loads).

The geometry model contains a representation of the gondola (similar to the GRIS Supernova configuration) that supports the instrument assembly via an adjustable elevation trunion mechanism/structure. The thermal model consists of 4”x4”x$^1/_8$” aluminum angle painted white and is shown in Figure 1 below:

[1] Cullimore and Ring Technologies, Inc. Thermal Desktop 3.3 Beta Release 4

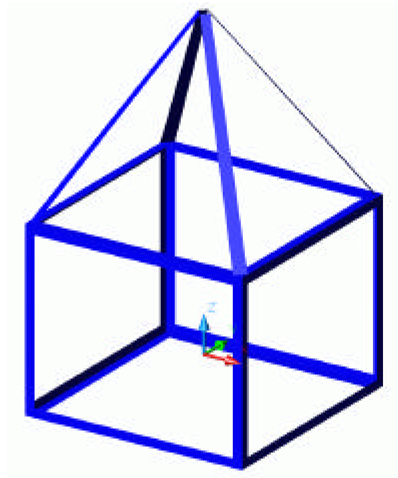

Figure 1 - GLAST Gondola Model (Shaded)

This gondola model mostly serves as a solar/IR blockage for the instrument pressure vessel. Conduction connectors (8 each @ 1 W/ºC) were added between the pressure vessel and the gondola to simulate the structural conductive coupling between these two assemblies.

The pressure vessel/bellyband assembly was modeled as a combined right circular cylinder with spherical end caps 91" tall and 42 $^{7}/_{8}$" in diameter. The bellyband (blue) is $^{5}/_{16}$" thick aluminum 8" tall and 42 $^{7}/_{8}$" in diameter. The pressure vessel (green, 2 ends) are $^{1}/_{8}$" thick aluminum, bare metal on the inside, covered with 2-¼" thick foam and painted white on the outside. The bellyband is bare aluminum on the inside and painted white on the outside (no insulation). The combined pressure vessel and bellyband model is shown in Figure 2 below:

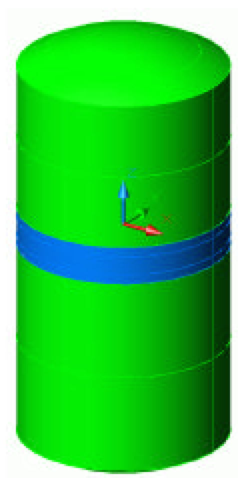

Figure 2 - GLAST Pressure Vessel and Bellyband Model (Shaded)

The insulation on the pressure vessel is not visible because the insulation is handled mathematically in the model with offset node numbers and conduction connectors between the inner and outer surfaces of the vessel.

The bellyband (blue) shares nodes with two ¼” bare aluminum (both sides) bulkheads (also blue) that contain a 23½” square hole in the center as shown in Figure 3 below:

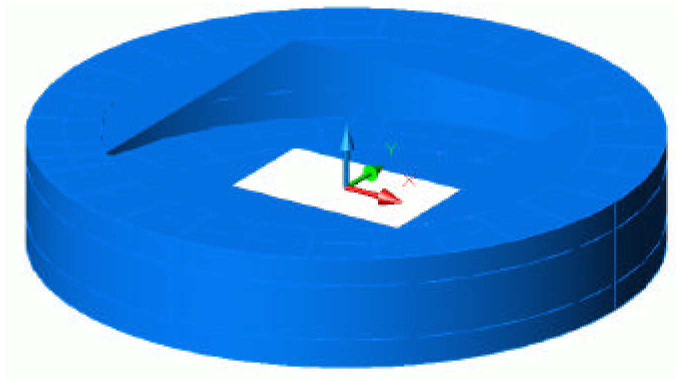

Figure 3 - GLAST Bulkheads Model (Shaded)

Mounted to the upper side of the lower bulkhead is a 26”x26”x$^3/_4$” bare aluminum (both sides) plate to which the calorimeter (magenta) is mounted. The calorimeter is represented as an 8-noded box, exterior painted white (convection dominant), 20” square and 8” tall. The calorimeter receives a constant heat load of 15W, applied to the solid core. The core material is 70% solidity aluminum to achieve the100 kg mass. An interface conductance of 100 W/m^2-ºC was established between the calorimeter mounting plate and the lower bulkhead. The same interface conductance was used between the calorimeter lower surface and the mounting plate.

The XGT+ACD+TKR (light green) is modeled as an 8-noded box, exterior painted white (convection dominant), 19” square and 32” tall. The XGT+ACD+TKR receives a constant heat load of 45W, applied to the solid core. The core material is 10% solidity aluminum to achieve the 50 kg mass. The XGT+ACD+TKR is “floating” above the calorimeter within the angle support structure with 4 each @ 1 W/ºC conduction connectors between the lower nodes and nodes on the upper bulkhead.

The electronics rack (red) is modeled as an 8-noded box, exterior painted white (convection dominant), 19”x23”x23” tall. The electronics rack receives a constant heat load of 320W, applied to the solid core. The core material is 15% solidity aluminum to achieve the 70 kg mass. The electronics rack is “floating” below the calorimeter mounting plate within the angle support structure with 4 each @ 10 W/ºC conduction connectors between the lower nodes and the angle support structure (orange).

The entire assembly, with the bellyband, bulkheads, calorimeter, mounting plate, XGT+ACD+TKR, and electronics rack (without the gondola and pressure vessel) is shown in Figure 4 below:

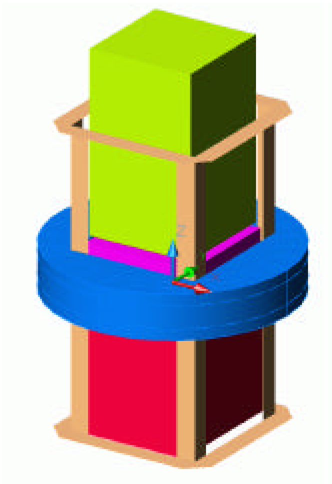

Figure 4 - GLAST Structure and Electronics (Shaded)

An overall wire frame view of the thermal model (including balloon) is shown in Figure 5 below:

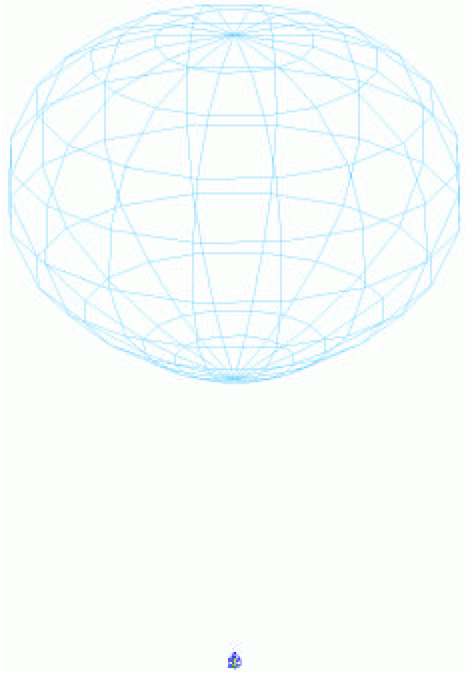

Figure 5 - GLAST Complete Thermal Model (Wire Frame)

The balloon dominates the image above with the payload represented as the extremely small object at the bottom of the image. With the balloon removed from the image, the wire frame of the payload can be viewed in more detail as in Figure 6 below:

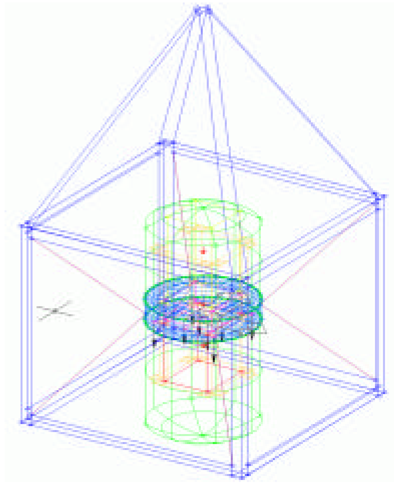

Figure 6 - GLAST Payload Thermal Model (Wire Frame)

With the gondola and conduction connectors to the pressure vessel removed, a more detailed wire frame of the pressure vessel and its contents can be viewed in Figure 7 below:

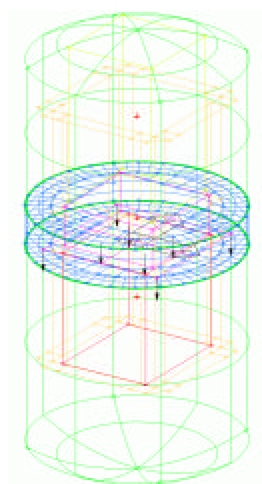

Figure 7 - GLAST Pressure Vessel Thermal Model (Wire Frame)

The black arrows represent the area-based interface conductance applied to the bottom of the calorimeter and mounting plates. It is assumed that the pressure vessel and its contents remain in the vertical position (as shown) for the duration of the flight.

2.2. Environment

The summer 2001 GLAST test flight will be launched on June 15, 2001 from Palestine, TX (31° 47' N, 95° 38' W) at sunrise (6:00AM local). In flight, the payload will be able to rotate freely. In the thermal model, the payload rotates four (4) complete revolutions with respect to the Earth. The payload will ascend at a constant rate of 1000 ft/min to a float altitude of 120kft (36.6 km) through a standard[2] atmosphere as shown in Figure 8 below:

[2] U.S. Standard Atmosphere Supplements, 1966, 30°N July

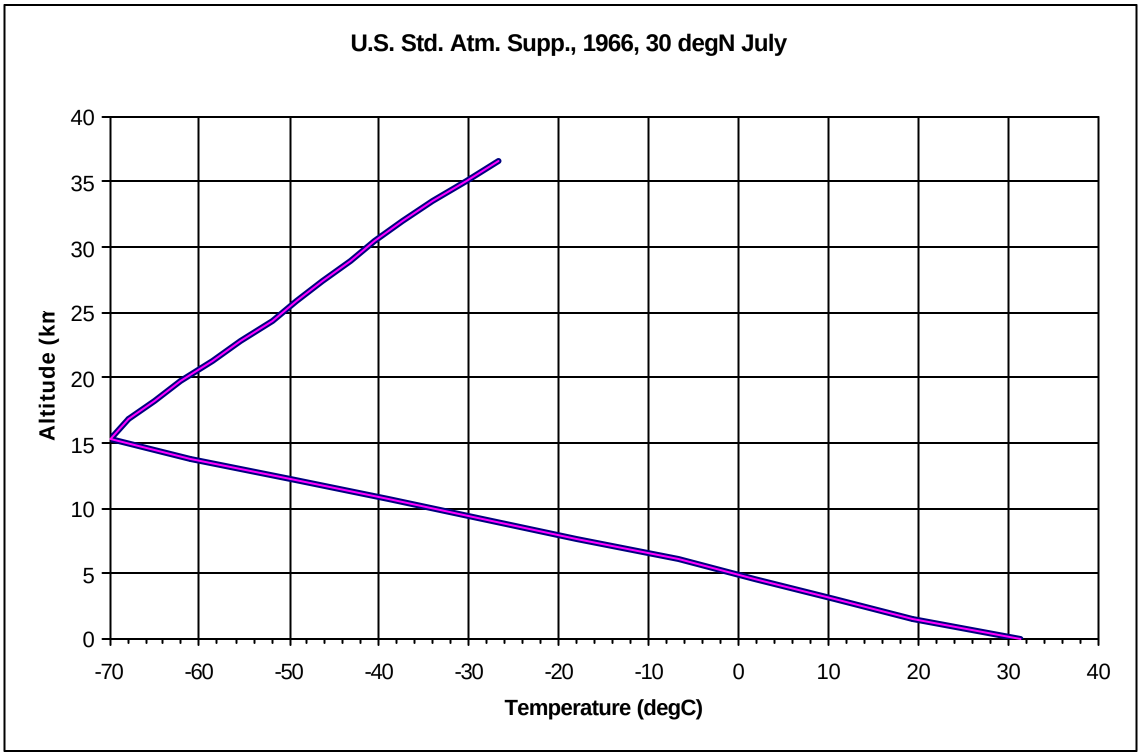

Figure 8 - U.S. Std. Atm. Supplement, 1966, 30N July, Temperature Profile

The payload will maintain this float altitude for a maximum of 10½ hours and will be terminated at or before sunset (6:30PM) that same day, with no day/night transition. Under hot case conditions (hot cloudless desert surface), the albedo and longwave radiation (LWR) values will be 0.40 and 280 W/m^2 (-8.0ºC) respectively. Under cold case conditions, the albedo and LWR values will be 0.30 and 160 W/m^2 respectively. Atmosphere-diffused solar flux is ignored. The solar flux will be derived from the 3.3% seasonal variation of the 1353 W/m^2 standard given by:

Solar Flux = S (1+0.033[cos {360n/365}]);
Where S=1353W/m^2 and n is nth day of year

Given that June 15, 2001 is the 166th day of the year, the solar flux used will be 1310 W/m^2.

2.3. Initial Conditions

It is assumed that the initial (launch) temperature of all nodes in the thermal model (geometry and air inside pressure vessel) is 20ºC. These temperatures are allowed to adjust in the nodal network transient solution for the remainder of the flight simulation. No "ground condition" steady state calculations are made to initialize temperatures. The initial air temperature (outside the pressure vessel) is 31.43ºC[3].

[3] U.S. Standard Atmosphere Supplements, 1966, 30°N July, 0m geometric altitude

2.4. Convection

It is assumed that the pressure vessel is pressurized with dry nitrogen to 1 atmosphere (no significant pressure differential inside versus outside) prior to launch, which is maintained with an effective gas make-up system during the flight. The thermal model assumes the pressure vessel is divided into two plenums (one air node each), above and below the belly section.

Fluid movement within each plenum is assumed to be 20CFM. Given the geometry of the vessel, the average air velocity inside each plenum is calculates[4] to be 4 ft/min. At this velocity, standard conditions, parallel and laminar flow, the average convective heat transfer coefficient over a flat plate calculates[5] to be 0.46 W/(in^2-ºC). Convection conductors with this magnitude will be connected between all interior surfaces and each of the two air nodes. The total thermal mass of the air inside the pressure vessel is calculated[6] to be 2518 joule/K. Of course, this is split between the two air nodes.

Fluid movement between plenums is also assumed to be 20CFM total (inlet and return). The heat capacity transferred is calculated[7] to be 22 W/ºK. This convection conductor will be connected between the upper/lower air nodes and can be set to zero to accomplish “turning off” the fan.

The exterior air node is defined as a boundary node (infinite heat capacity) with temperature as is defined in Figure 8 above. The convection heat transfer coefficient from this node to the external surfaces of the thermal model, calculated in a similar manner to that for the internal convection coefficient[5], depends upon a number of factors (altitude, temperature, ascent velocity, properties of air at certain altitudes and temperatures, etc.). These calculations generated an area-based convective heat transfer coefficient as a function of altitude as shown in Figure 9 below:

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[4] Total cross-sectional area is 1444 in^2 or 10 ft^2. Half of this area is assumed for flow in each of two directions. At 20 CFM, velocity is 20 CFM / 5 ft^2 = 4 ft/min.

[5] Assume published properties of air at 300K and 2ft characteristic length:

$$V := 4\cdot\frac{ft}{min} \quad L := 2\cdot ft \quad k := 26.3\cdot\frac{watt}{m\cdot K} \quad Pr := 0.707 \quad \nu := 15.89\cdot 10^{-6}\cdot\frac{m^2}{s} \quad Re := \frac{V\cdot L}{\nu} \quad Re = 779.551$$

$$Nu := 0.664\cdot Re^{\frac{1}{2}}\cdot Pr^{\frac{1}{3}} \quad Nu = 16.516 \quad h := \frac{Nu\cdot k}{L} \quad h = 0.46\,\frac{watt}{in^2\cdot K}$$

[6] The heat capacity of the air inside the pressure vessel is calculated by:

$$H := (46.5 + 8 + 36.5)\cdot in \quad dia := 42.875\cdot in \quad Vol := \pi\cdot\frac{dia^2}{4}\cdot H \quad C_p := Vol\cdot\rho\cdot c_p \quad C_p = 2.518\times 10^3\,\frac{joule}{K}$$

[7] The 20 CFM of air also returns for double the effect:

$$V_{dot} := 20\cdot 2\cdot\frac{ft^3}{min} \quad \rho := 1.1614\cdot\frac{kg}{m^3} \quad c_p := 1007\cdot\frac{joule}{kg\cdot K} \quad q_{dot} := V_{dot}\cdot\rho\cdot c_p \quad q_{dot} = 22.078\,\frac{watt}{K}$$

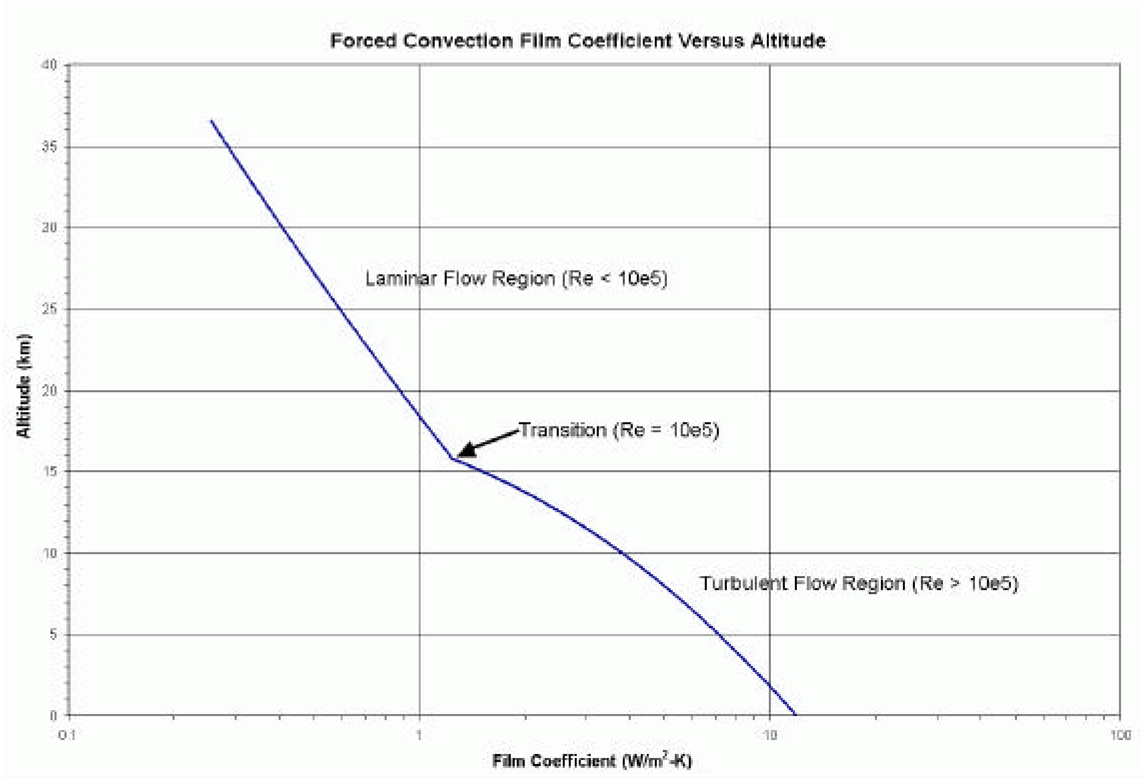

Figure 9 - GLAST External Convective Film Coefficient

When the balloon begins its 1000 fpm ascent, the external flow boundary layer is assumed turbulent ($Re_x > 5x10^5$) until an altitude of approximately 52,000 ft (15.8 km) where the transition to laminar flow occurs. At float altitude, after the balloon has stopped its ascent, a free convection film coefficient of 0.1 W/(m^2-ºC) is used. This area-based convective connector value is placed on surfaces that have only one side exposed to the air stream. The convective connector value is doubled on surfaces that have both sides exposed to the air stream such as the gondola frame.

2.5. Temperature Limits

The nominal detector temperature target is 20ºC and limits are +10 to +30ºC. The allowable survival detector temperature limits are +5ºC to +35ºC.

3. Hot Case Results and Discussion

As per Gary Godfrey's Jan 24, 2001 calculations, if it is assumed the pressure vessel is perfectly insulated (adiabatic), a 1200lb mass (assume properties of aluminum) dissipating 380W will see an average temperature rise of 22.3ºC over an 8-hour period, or an average temperature rise of 2.8ºC per hour. For the purposes of this analysis, revised calculations were made based upon the thermal model geometry as shown in the spreadsheet below:

Component	Mass (kg)		Power (W)	
Pressure Vessel	280		0	
XGT+ACD+TKR	50		45	
Calorimeter	100		15	
Electronics	70		320	
Structure				
Calorimeter Mtg Plate	23		0	
Upper Bulkhead	16		0	
Lower Bulkhead	16		0	
Bellyband	15		0	
Trunion				
Flanges (2)	4		0	
Legs (4)	8		0	
Totals:	582	Kg	380	J/sec
	1284	Lbs		
Specific Heat	900	J/kg-degC		
Heat Capacity	524107	J/degC		
Temperature Rise	2.61	degC/hr		

In this calculation, a total mass of 1284lbs was obtained and the resulting temperature rise was 2.6ºC per hour. The temperature is therefore highly transient and is expected to climb steadily throughout the flight. The flight temperature is very much dependant upon the temperature at launch. If the lower temperature limit is +10ºC and the upper limit is +30ºC and it is assumed the components are at +10ºC at launch, the average temperature can only rise 1.6ºC per hour to stay within the temperature limits. In order to achieve this, it is expected that a significant heat loss must be realized.

With an exposed bellyband, conductance through the elevation mechanism and imperfect insulation, the actual temperature rise will be less than this ideal adiabatic value. In addition, heat will be absorbed into the exterior surfaces in the form of direct, diffuse and reflected solar radiation and LWR from the earth. The direct solar flux is attenuated near solar noon when the balloon film shades the gondola. Heat will also be lost from the exterior surface through convection to the atmosphere and radiation to space. The following several representative temperature time-history plots (Figure 10 thru Figure 19) will indicate how the temperature of major parts of the payload vary over the flight under hot case conditions when all of these factors are figured in and the payload is configured as described:

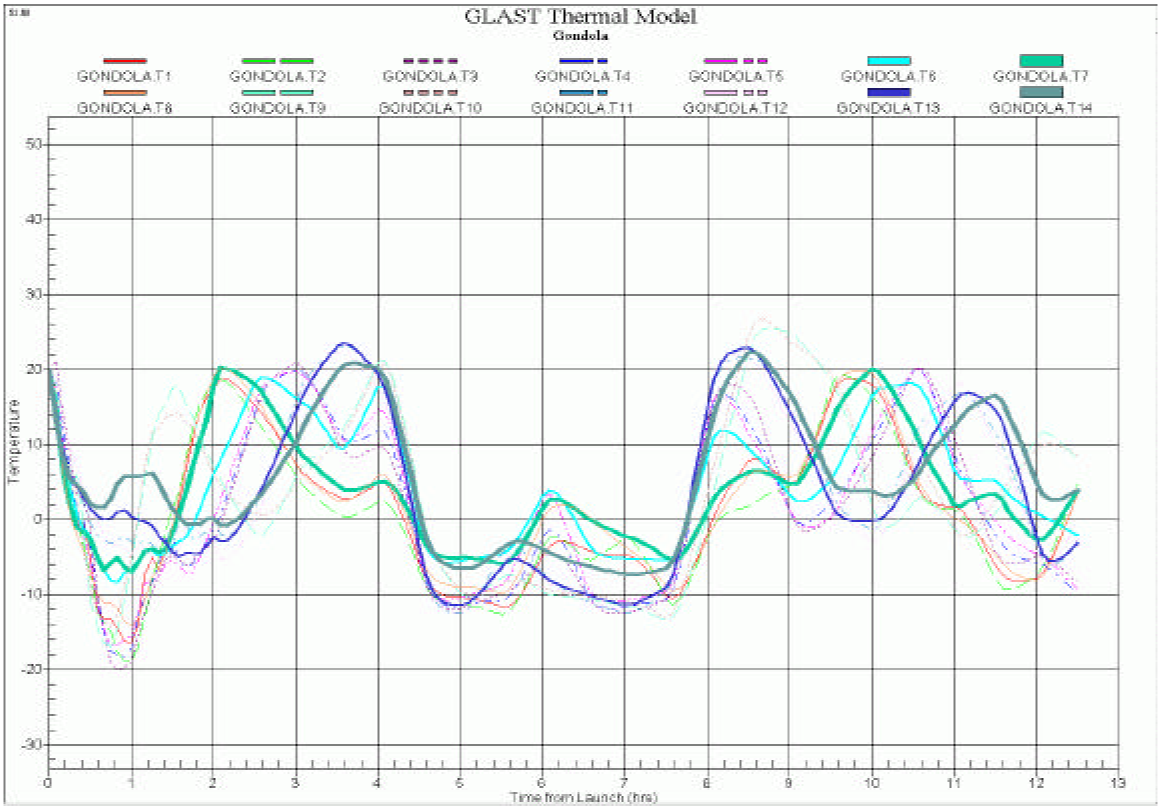

Figure 10 – GLAST Representative Gondola Temperatures – Hot Case

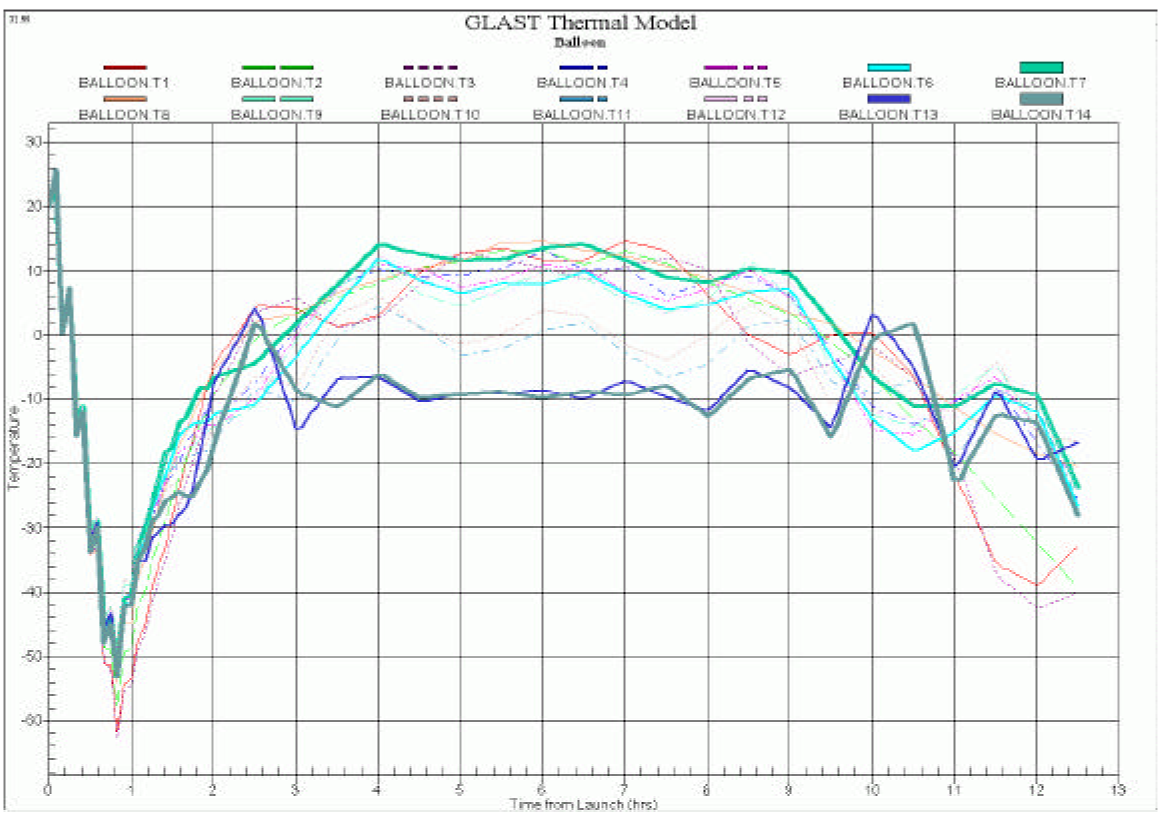

Figure 11 - GLAST Representative Balloon Temperatures – Hot Case

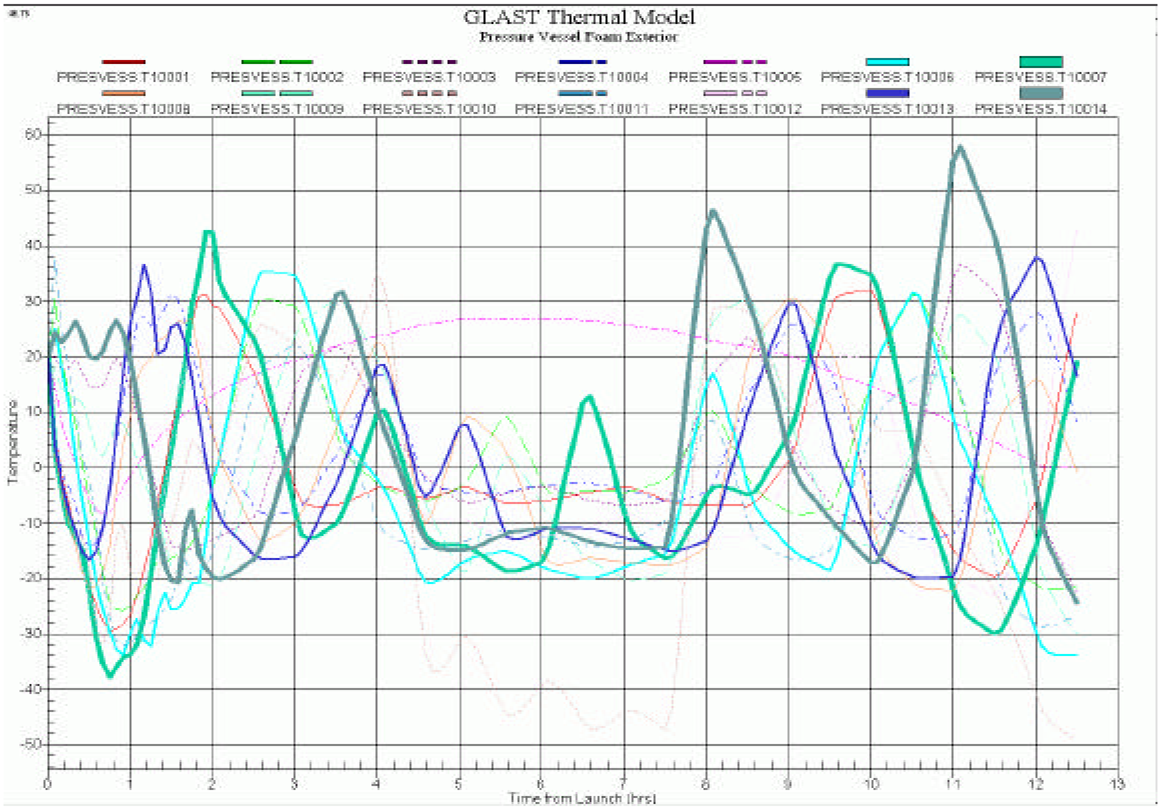

Figure 12 - GLAST Representative Pressure Vessel Foam Exterior Temperatures – Hot Case

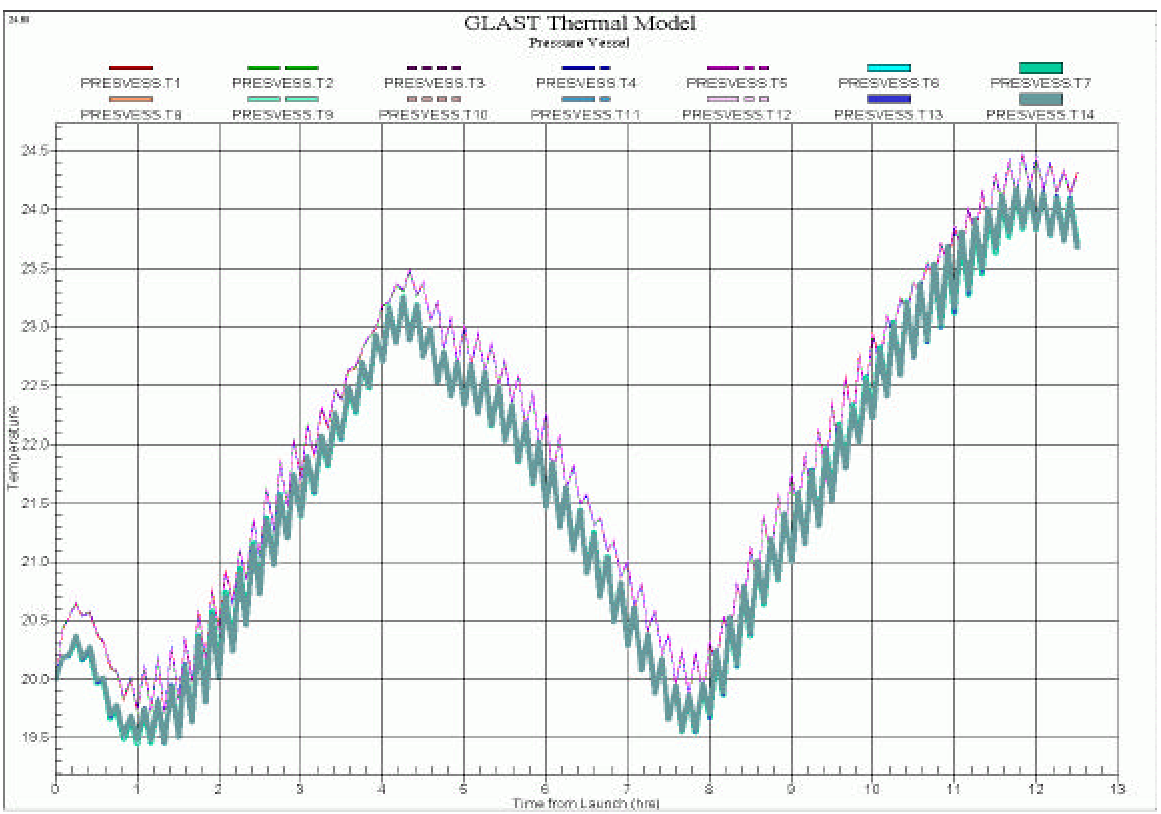

Figure 13 - GLAST Representative Pressure Vessel Temperatures - Hot Case

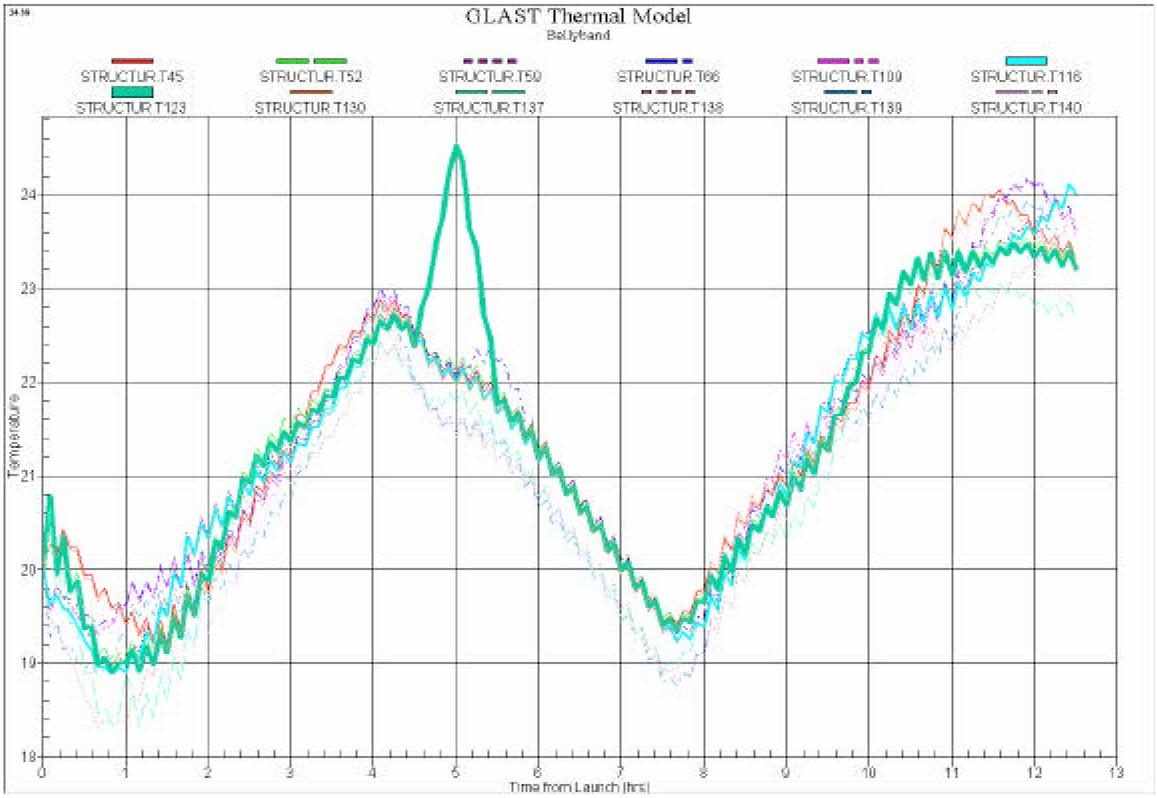

Figure 14 - GLAST Representative Bellyband Temperatures - Hot Case

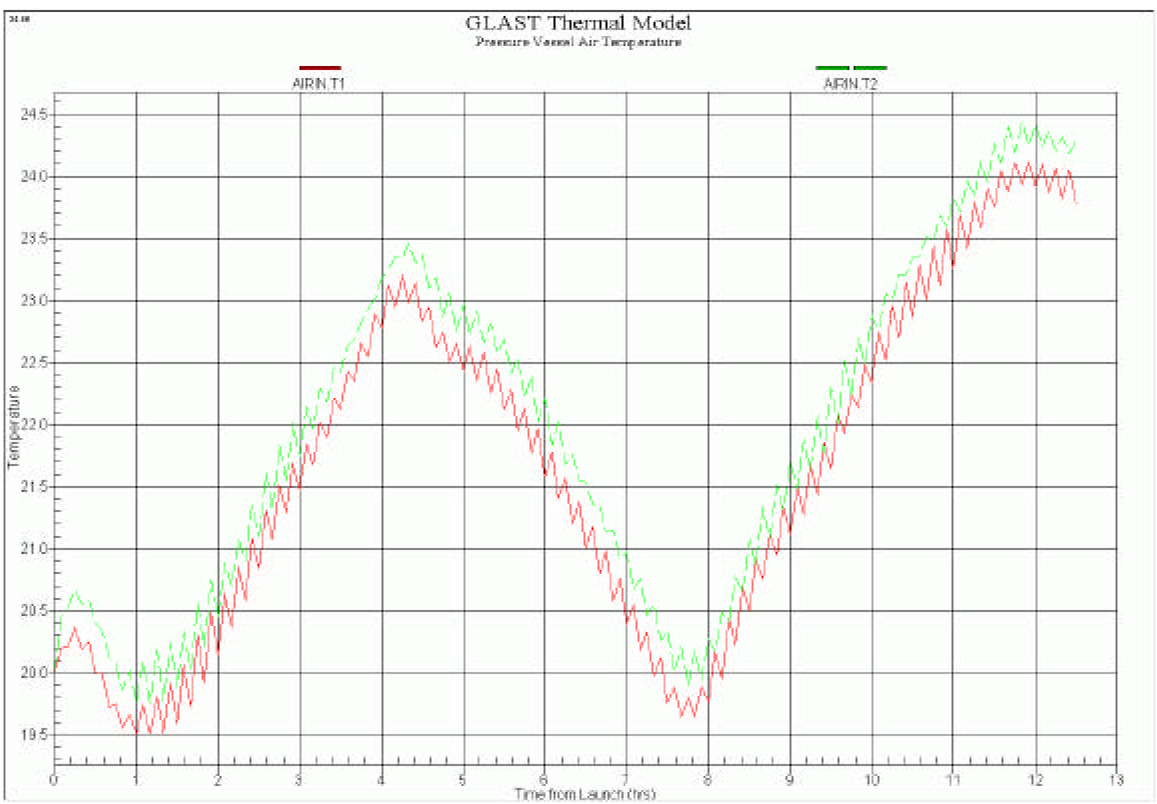

Figure 15 - GLAST Pressurized Inside Air Temperature - Hot Case

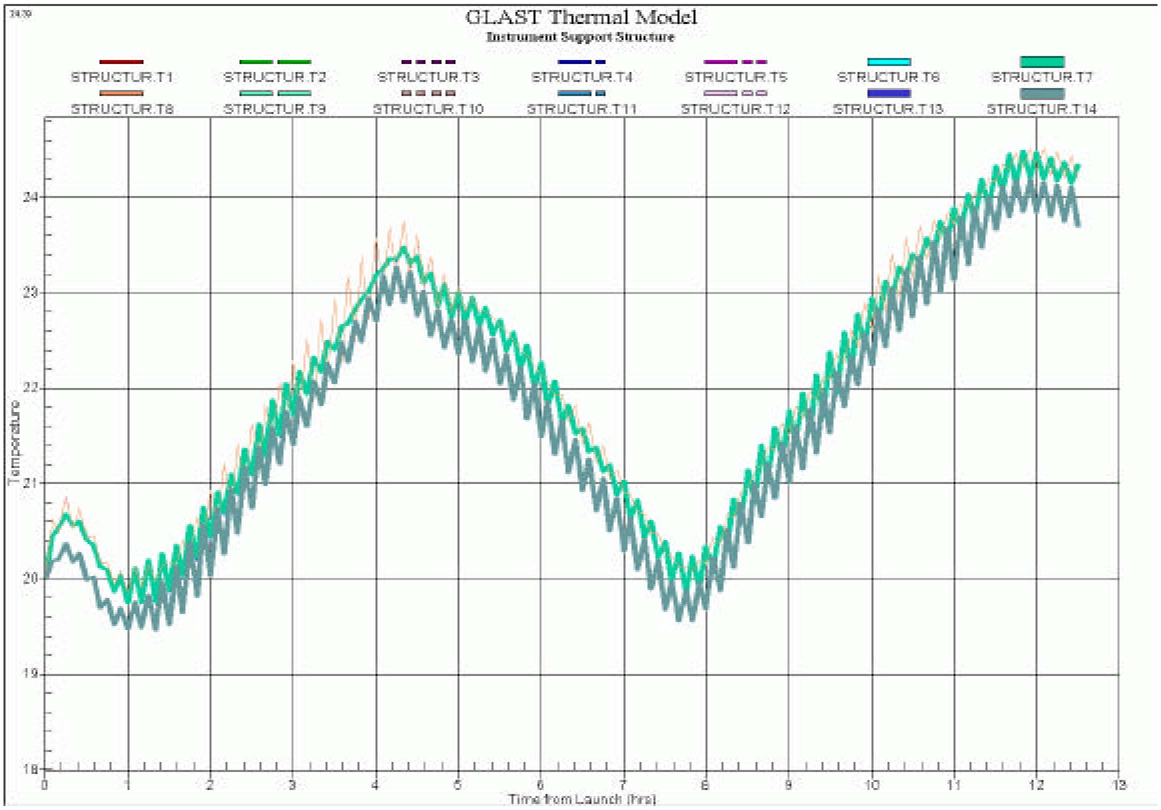

Figure 16 - GLAST Representative Instrument/Electronics Support Structure Temperatures - Hot Case

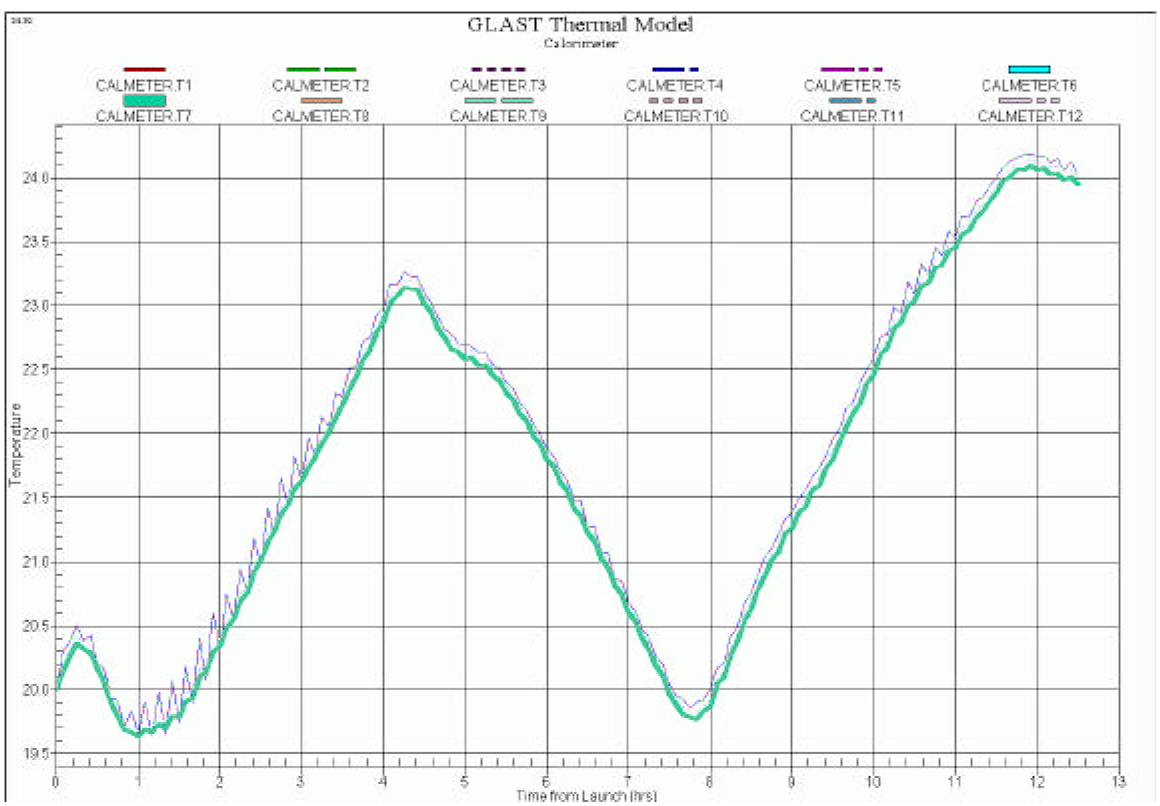

Figure 17 - GLAST Representative Calorimeter Temperatures - Hot Case

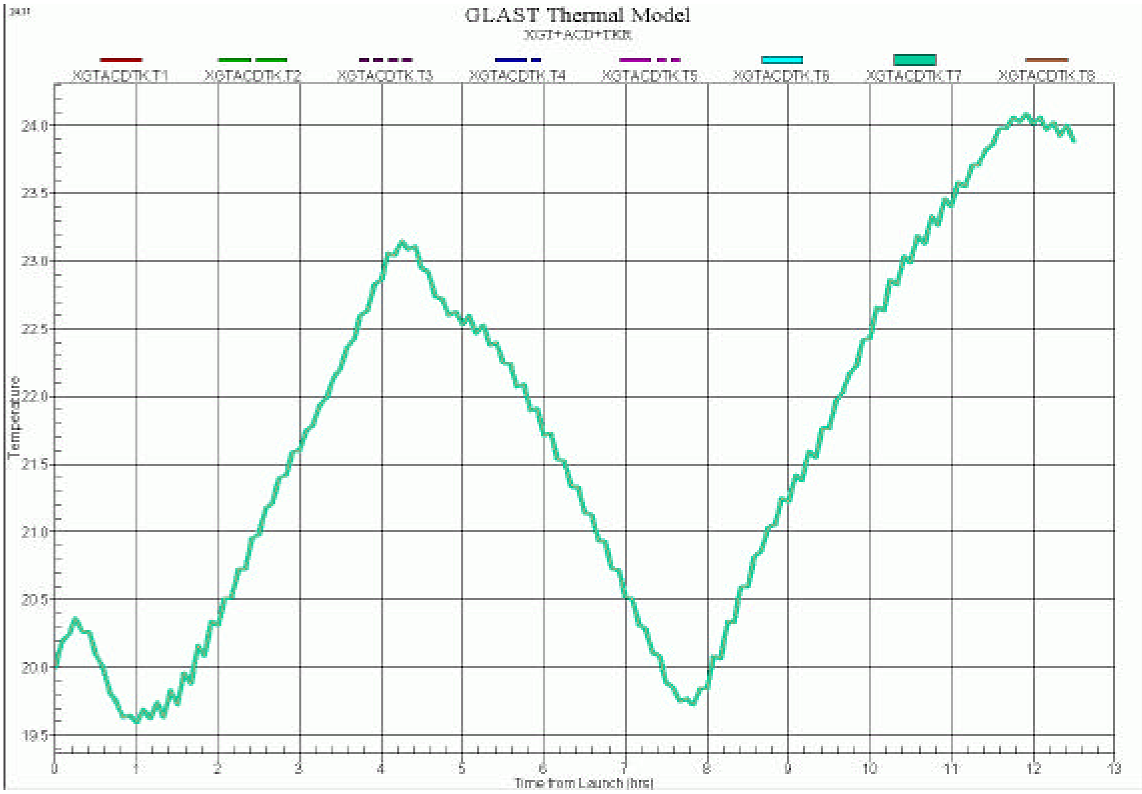

Figure 18 - GLAST Representative XGT+ACD+TKR Temperatures - Hot Case

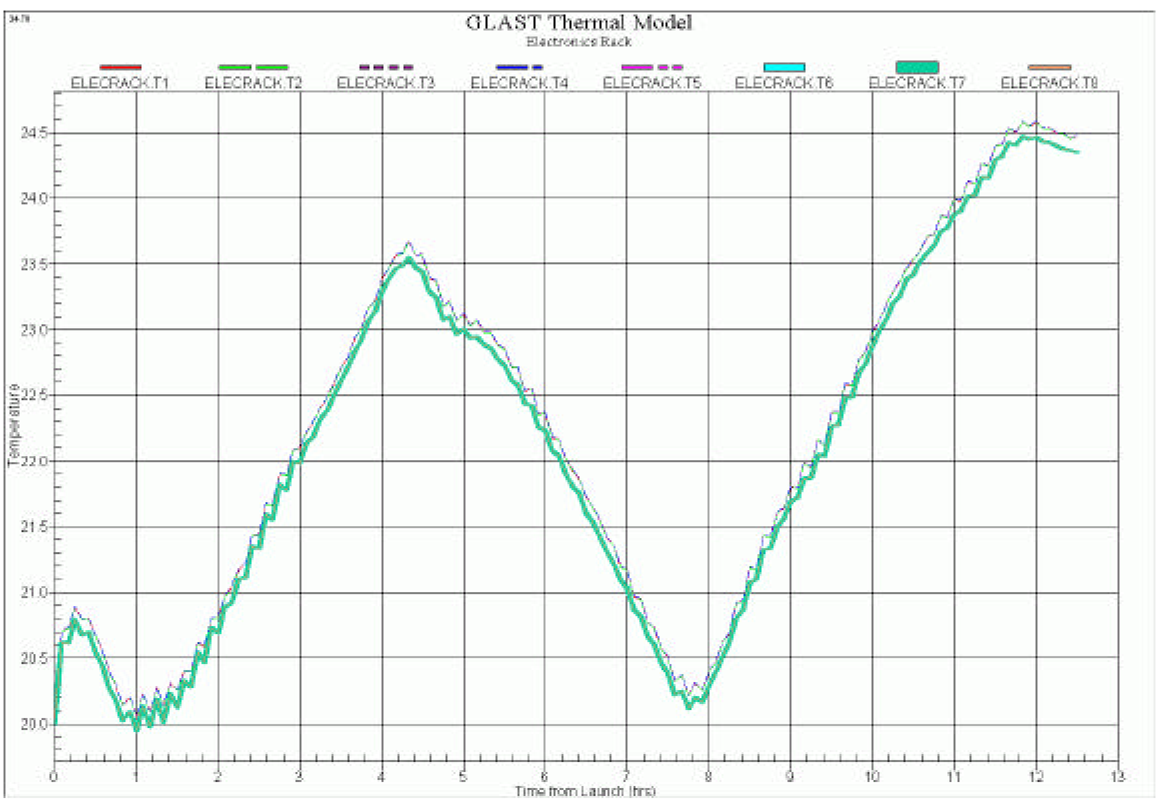

Figure 19 - GLAST Representative Electronics Rack Temperatures - Hot Case

As can be seen from the plots, the initial temperature of all nodes in the thermal model is 20ºC. The launch temperatures are critical because, under the given configuration, the temperatures will only rise during the flight as a result of the heat build-up inside the pressure vessel. With the pressure vessel heavily insulated, the launch temperatures must be monitored closely.

A drop and recovery in temperatures can be observed during the first 2 hours (or so) of the flight. This effect is the result of convection to the atmosphere during ascent. After the ascent phase is over and the balloon is at float altitude, the temperature of the components inside the pressure vessel rise at nearly 1¼ºC per hour, less than the 2-2½ºC per hour predicted by the adiabatic calculation. Between 4 and 8 hours after launch, another significant drop in temperatures is observed. This results from the shading of the payload by the balloon at or near solar noon. As soon as the payload is again illuminated, the temperature begins to rise again at nearly the 1¼ºC per hour rate. As the afternoon wears-on and the solar angle and flux diminish, this rate of temperature rise decreases to about 1ºC per hour prior to sunset and termination. It is observed that the temperature does actually start to drop near the end of the flight, prior to termination. This effect coincides with sunset.

The overall temperature rise of the calorimeter is 4C, which is quite acceptable as long as the calorimeter launch temperature is above 10ºC and below 26ºC. If the instrument temperature is allowed to exceed 26ºC at launch, there will be a fair likelihood the upper temperature will be exceeded. If the instrument temperature is below 10ºC at launch, the lower temperature will has already been exceeded.

4. Cold Case Results and Discussion

The remainder of the representative temperature time-history plots (thru) will indicate how the temperature of major parts of the payload vary over the flight under cold case conditions when all of these factors are figured in and the payload is configured as described:

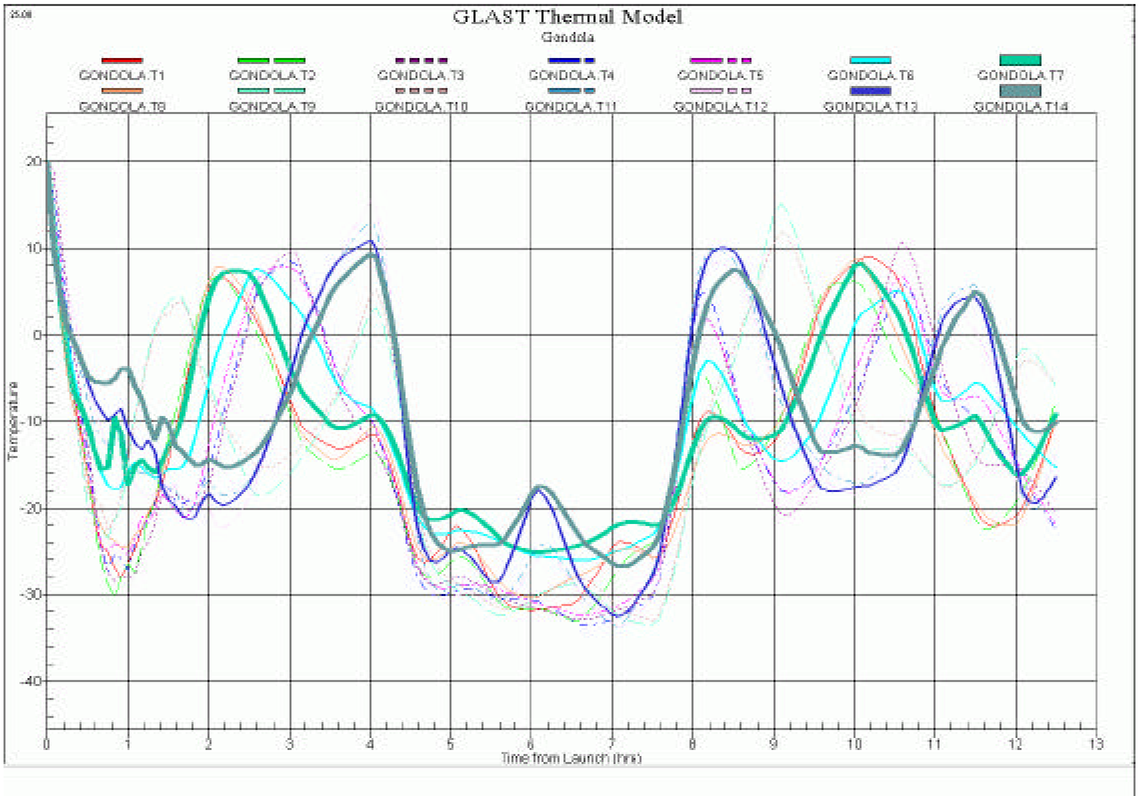

Figure 20 - GLAST Representative Gondola temperatures - Cold Case

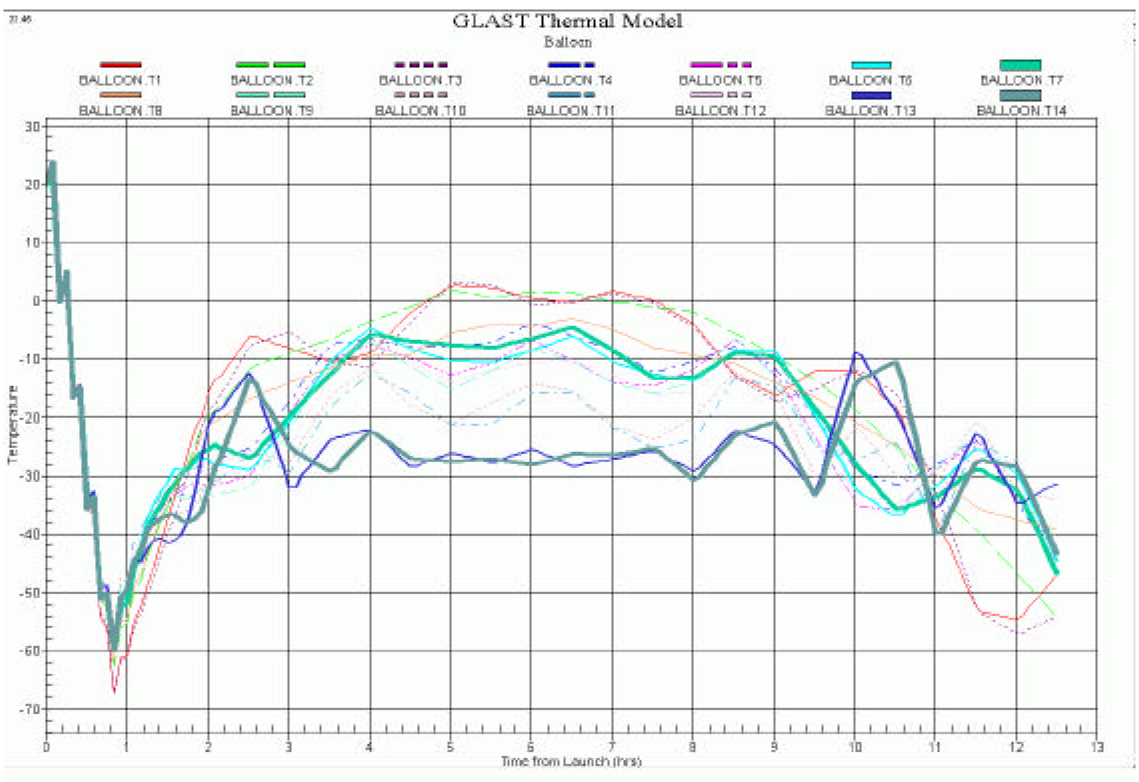

Figure 21 - GLAST Representative Balloon Temperatures - Cold Case

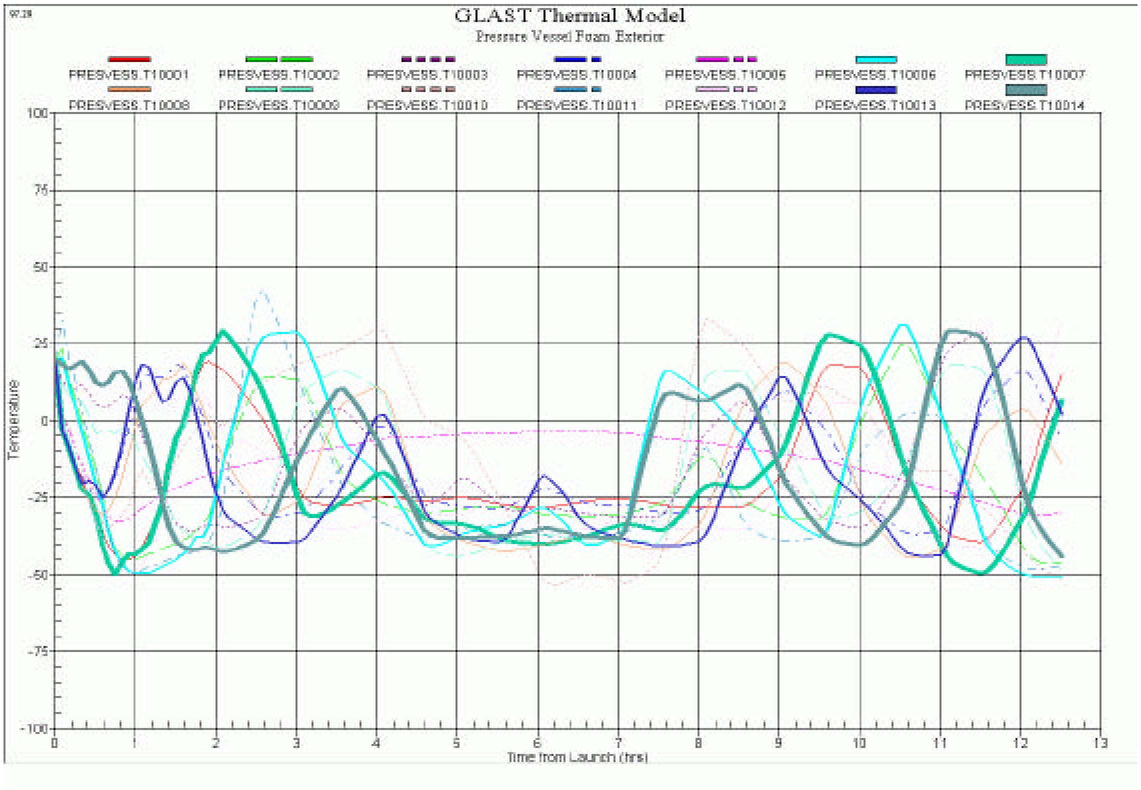

Figure 22 - GLAST Representative Pressure Vessel Foam Exterior Temperatures - Cold Case

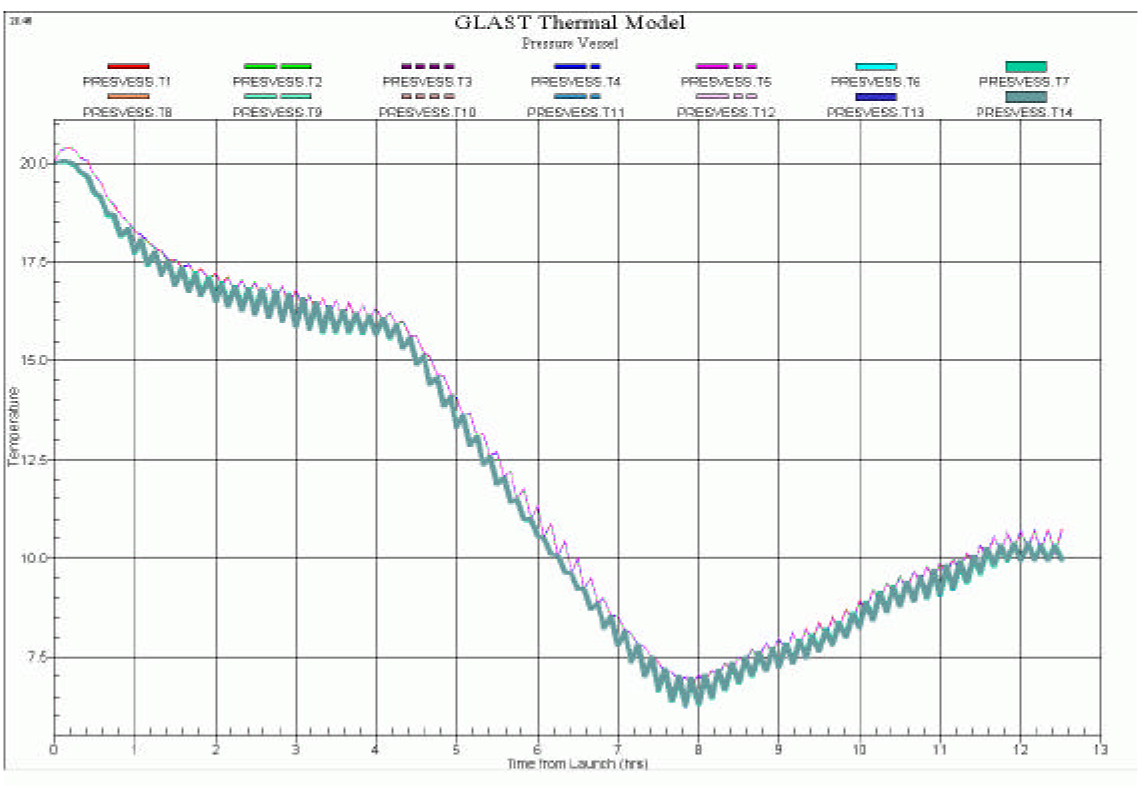

Figure 23 - GLAST Representative Pressure Vessel Temperatures - Cold Case

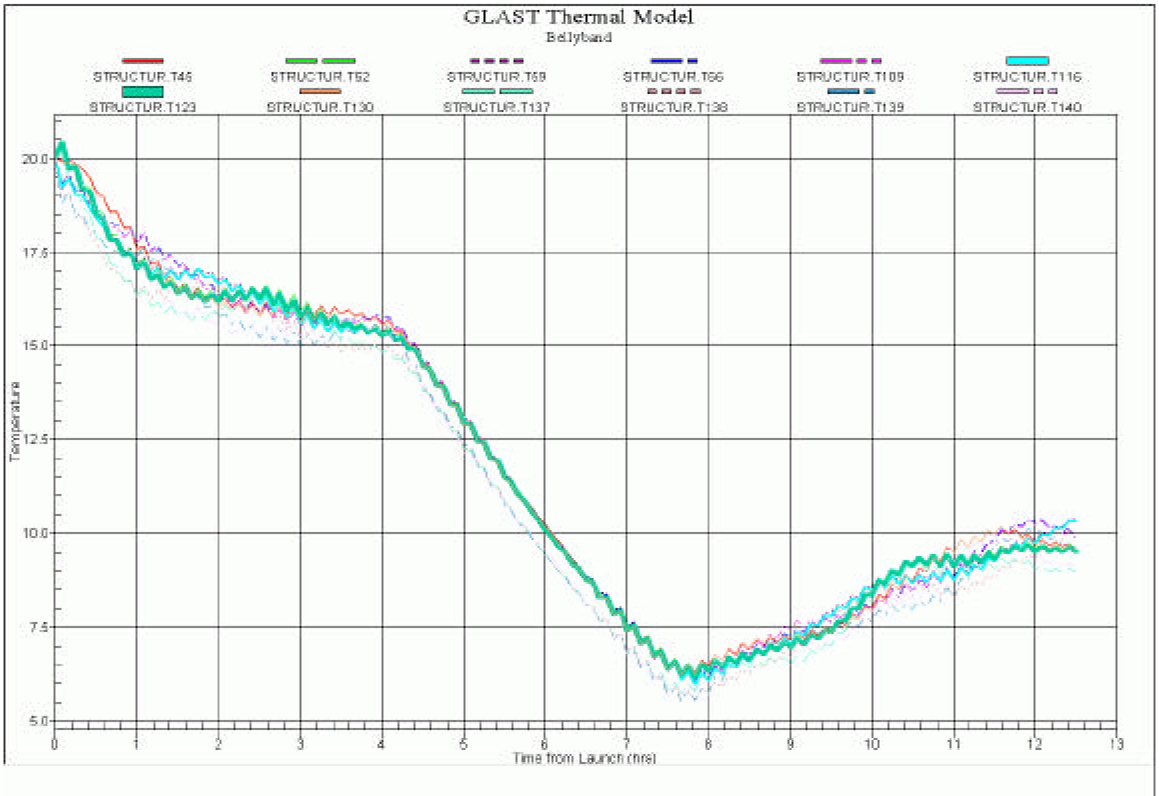

Figure 24 - GLAST Representative Bellyband Temperatures - Cold Case

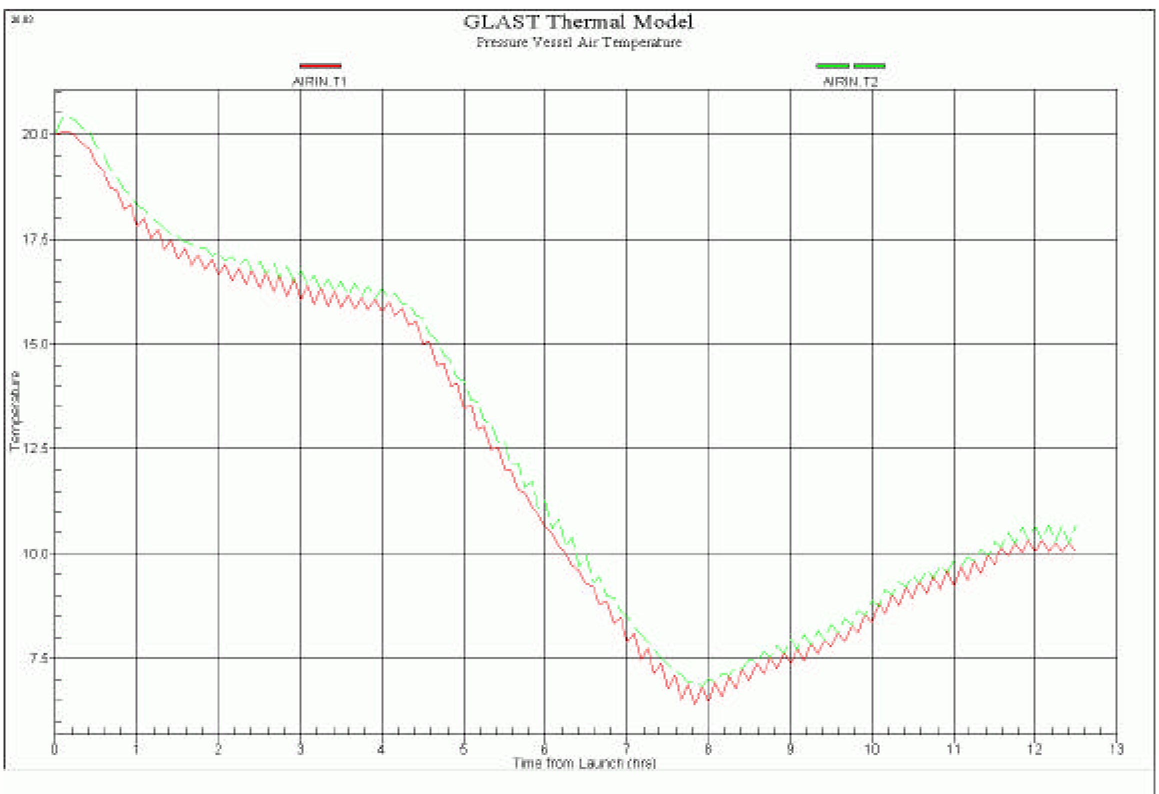

Figure 25 - GLAST Pressurized Inside Air Temperature - Cold Case

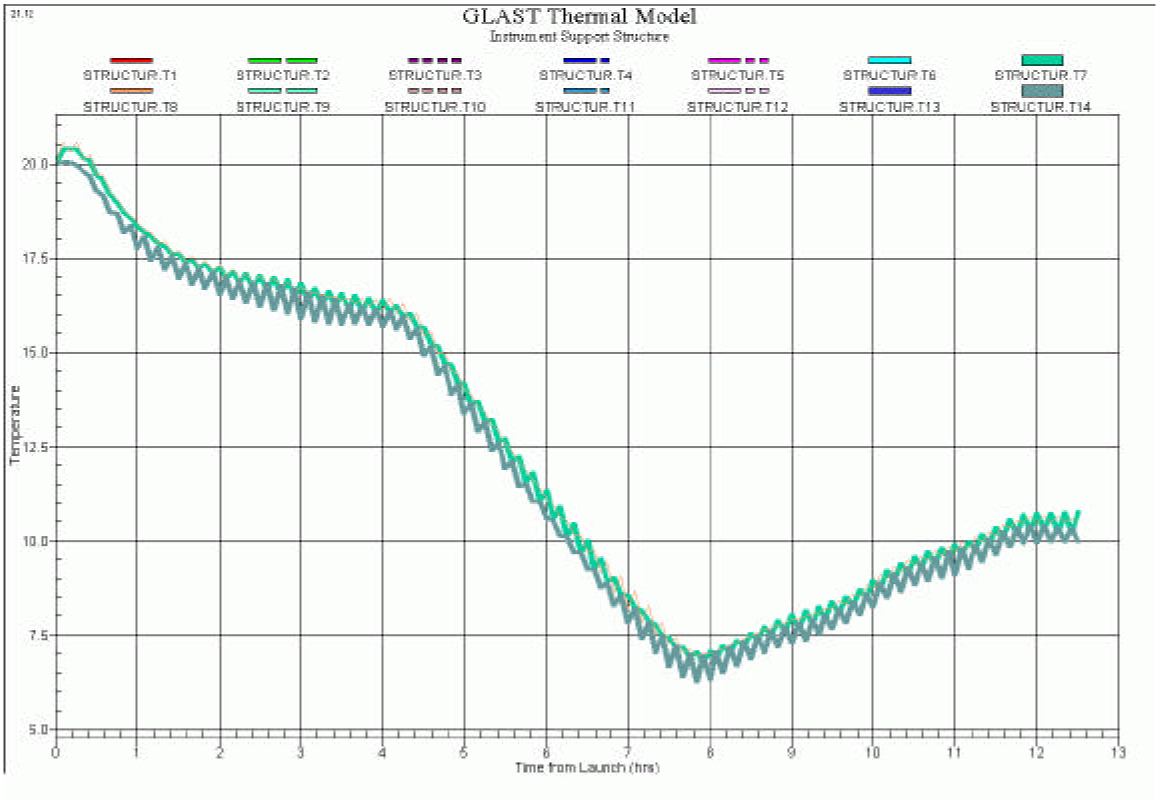

Figure 26 - GLAST Representative Instrument/Electronics Support Structure Temperatures - Cold case

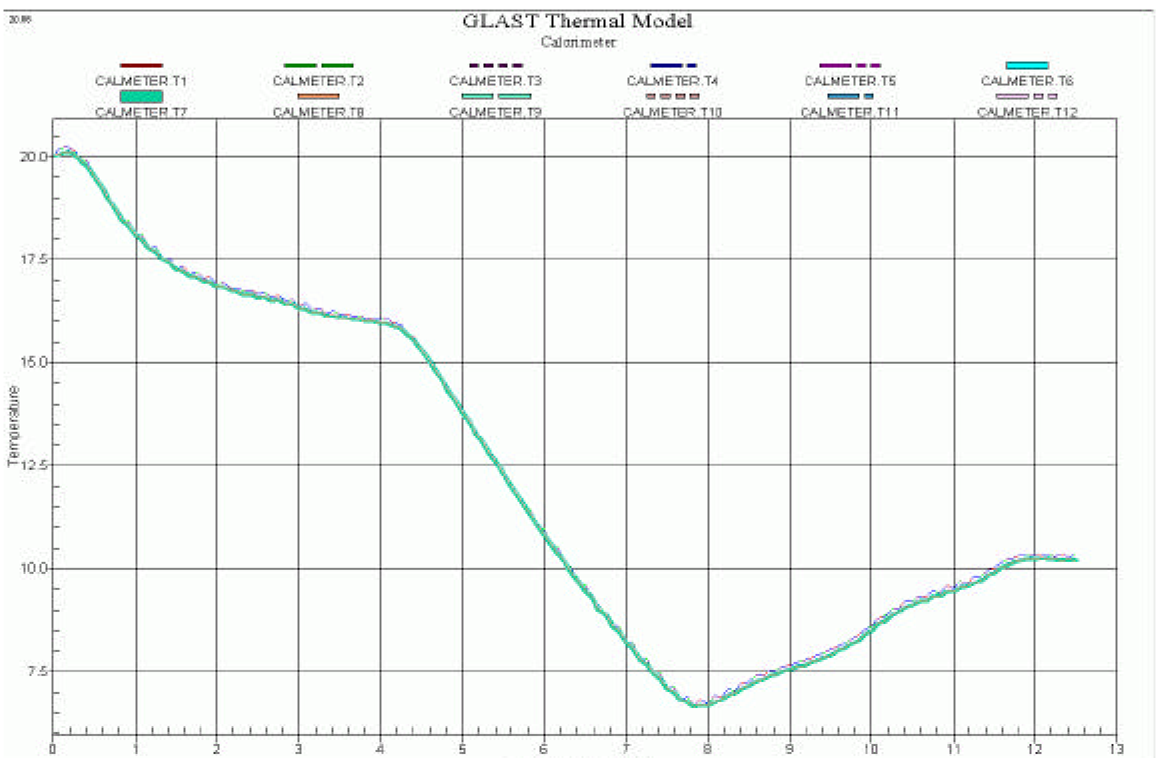

Figure 27 - GLAST Representative Calorimeter Temperatures - Cold Case

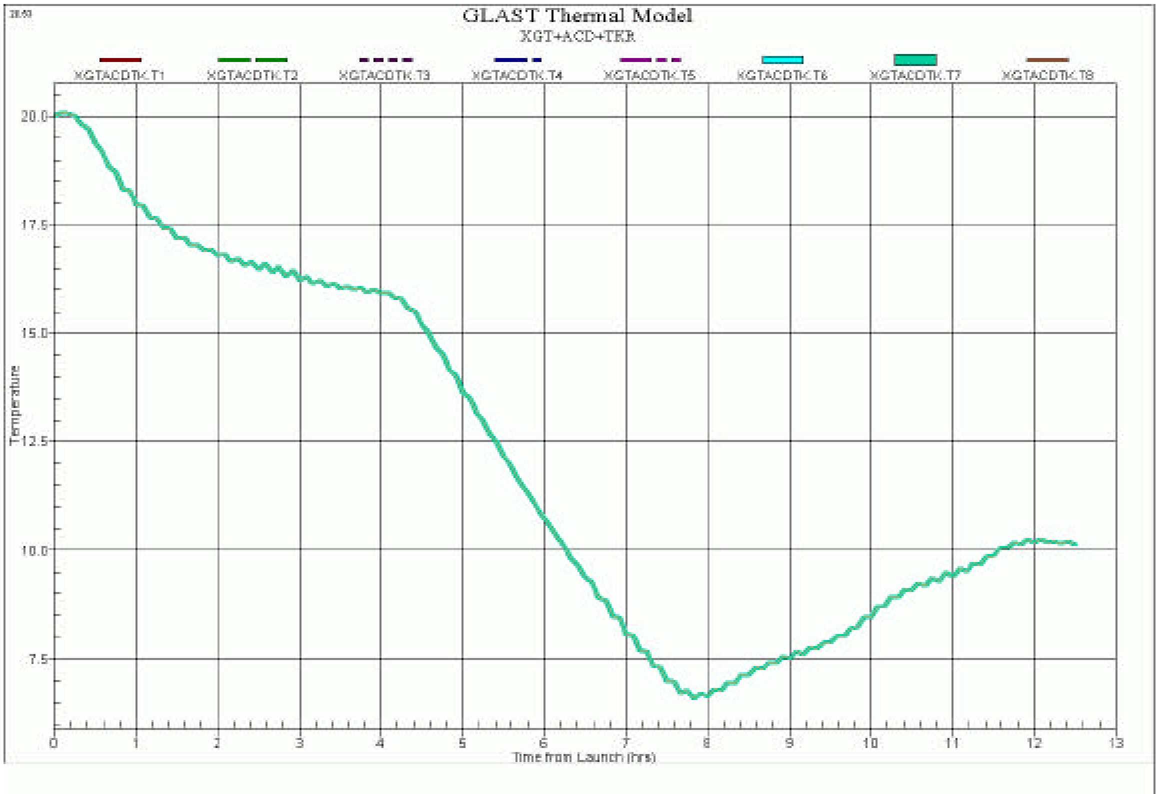

Figure 28 - GLAST Representative XGT+ACD+TKR Temperatures - Cold Case

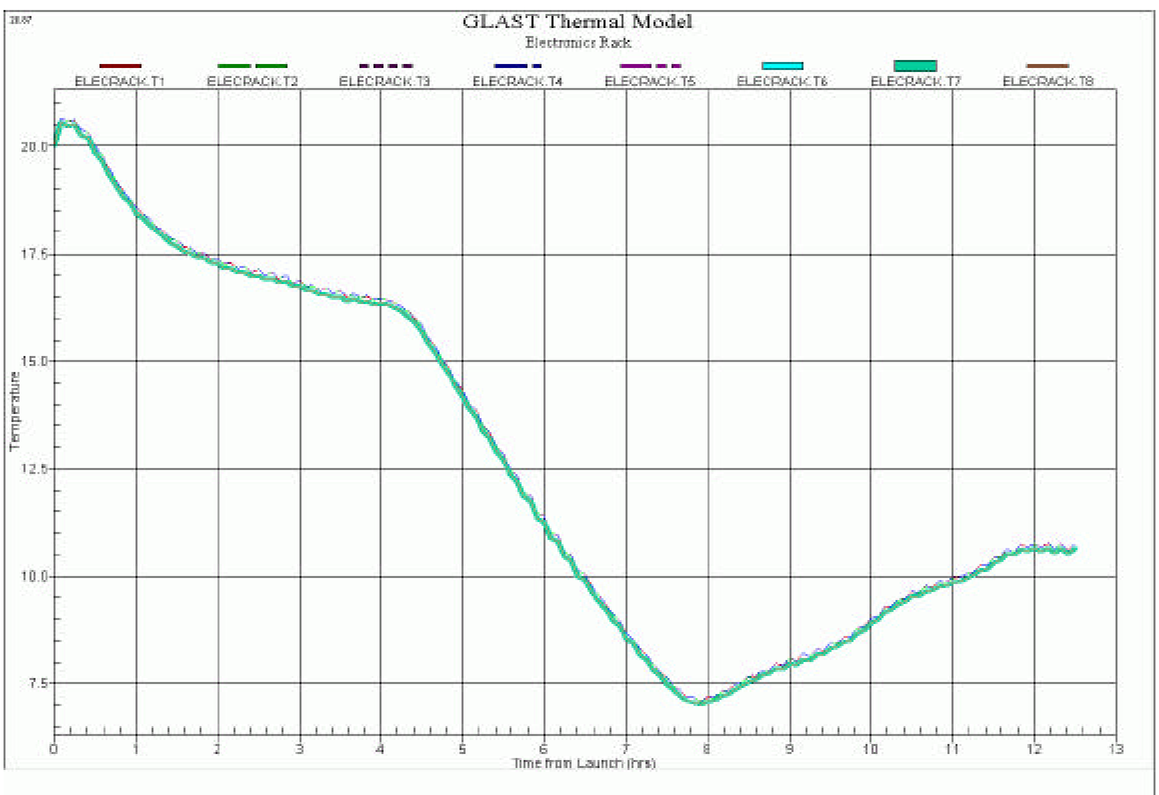

Figure 29 - GLAST Representative Electronics Rack Temperatures - Cold Case

Again, the initial temperature of all nodes in the thermal model is 20ºC. The launch temperatures are again critical because, under cold case conditions and the given configuration, the temperatures attempt to rise during the flight as a result of the heat build-up inside the pressure vessel but cannot overcome the combination of the convective cooling on ascent and the shading of the balloon from direct solar at solar noon. Only later in the afternoon does the temperatures have a chance to recover just prior to sunset and termination. Even with the pressure vessel heavily insulated, the launch temperatures must be monitored closely to insure they are not too cold.

A drop in temperatures due to ascent convection can be observed during the first 2 hours (or so) of the flight. Although the rate of temperature decline slows, the decline cannot be reversed before the payload is shaded from the sun by the balloon, dropping the temperature even further. As soon as the payload is again illuminated, the temperature begins to rise at nearly the $1^2/_3$ºC per hour rate. Again, it is observed that the temperature starts to drop again near the end of the flight, prior to termination. This effect coincides with sunset.

The overall temperature drop of the calorimeter is 13½ºC. This is acceptable as long as the calorimeter launch temperature is above 23½ ºC. If the instrument temperature is below 23½ ºC at launch, the lower temperature limit will be exceeded and survival mode will be required.

5. Thermal Design Recommendations

This thermal model predicts that when carefully configured, the GLAST payload can receive adequate thermal control using passive means as long as launch temperatures inside the pressure vessel are between 23½ºC and 26ºC. It is not expected that any elaborate, active thermal control measures will be required.

By making slight adjustments to the insulation properties (mostly thickness), the instrument can be held above the minimum temperature limit during initial ascent and heat build-up can be controlled during the flight. Because the pressure vessel is so well insulated, small changes can have a significant effect.

A detailed calculation should be made to attempt to assess the conduction path from the bellyband to the elevation bearing assembly and to the gondola. At times, the difference in temperature of the gondola and the bellyband can be as much as 30-35ºC. An error in the magnitude of the conduction connectors between the bellyband and the gondola could result in additional heat loss/gain through that path. The conduction connectors inside the pressure vessel are of minimal importance because of the convection resulting in temperatures being extremely uniform.

Due to the segmentation of the pressure vessel and unbalanced heat dissipation of the components inside, adequate air circulation is critical. It is recommended that duplicate circulation fans be installed to mitigate the risk of a fan failure and air circulation loss. This failure would cause the electronics to overheat and the other instrument components to cool.

This thermal model does not address the micro effects of the electronics enclosures such as the VME cards and the heat dissipating components. The thermal model reports an “average temperature” of the electronics in general. Certain portions of the electronics will be warmer than predicted and other portions may be cooler. It is critical that proper air circulation is maintained over the electronics.

The science organization should paint all (or severely limit the amount of) high α/ε (solar absorptance/IR emittance) ratio (mostly bare metal) surfaces exposed to direct or indirect solar radiation. Because of the high α/ε ratio, these surfaces absorb more solar energy than they can emit in the infrared, resulting in staggering heat retention and resulting daytime temperatures. Small areas like fasteners are acceptable as long as the heat retained in these surfaces can be efficiently conducted away to cooler points in the structure.

The gondola structure, elevation trunion mechanism and the exposed portion of the instrument bellyband represent exposed thermal radiators. The conduction from the protected portion of the bellyband to these structures should be minimized to reduce the amount of environmentally induced heat loss/gain from/to the instrument enclosure. This conductive decoupling can be accomplished by reducing the overall Fourier’s coefficient (kA/L) by selecting low-conductance interface materials, reducing cross-sectional area and increasing conductive path lengths (or any combination of these).

Recent soundings should be obtained for the Palestine atmosphere prior to launch and compared to the atmosphere profile used in this analysis. If the actual atmosphere profile (particularly at low altitudes and in the troposphere) is significantly different than that assumed in this analysis, the instrument may be either super-cooled or sub-cooled during the ascent.

6. Accuracy Risk

As a result of the limited (low-fidelity) nature of this thermal model, there is substantial accuracy risk associated with the results. This risk results from numerous potential localized thermal effects that are not well represented in a low-fidelity lumped-mass and nodal network representation. In order to support requirements development and validation, the GLAST team accepts this implicit risk for that purpose.

7. NASA Requirements

This thermal analysis may not necessarily fulfill NASA’s thermal system verification requirements prior to the flight, partly due to the limited fidelity and primarily because of the absence of NASA flight support equipment and mutual interaction in the model. NASA may or may not require a more detailed thermal analysis of the balloon system prior to flight.